National Aeronautics and Space Administration

Evolution of Extra-Terrestrial Mining Robot Concepts

SRR/PTMSS

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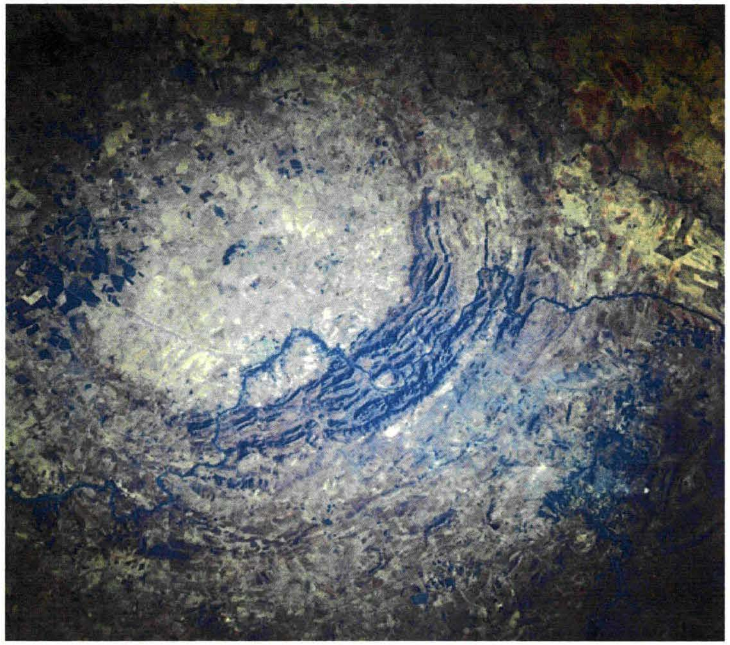
Terrestrial Impact Crater Mining for Resources

In 2007 the total global market capitalization of mining companies was reported at **US $962 billion**, (Businessweek, 2007)

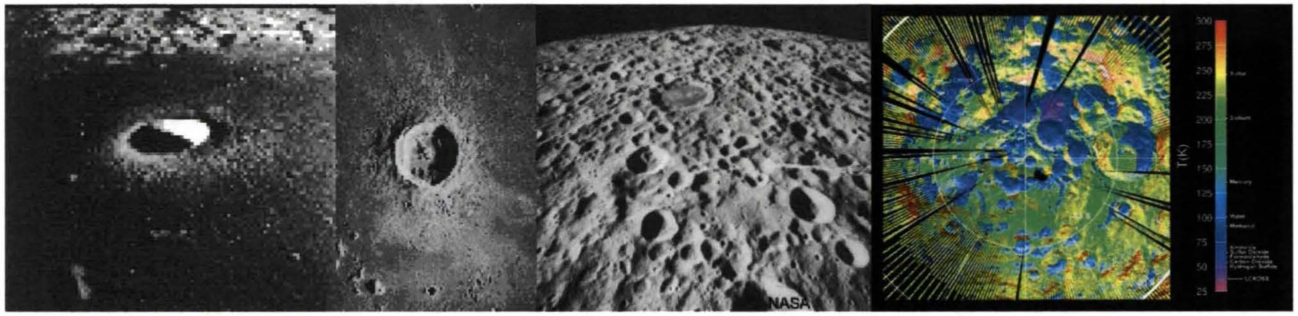


In North America alone, the value of impact related resources was in excess of **$18 billion/year** (1994 $)

Vredefort Crater – Largest known terrestrial impact crater 62 miles southwest of Johannesburg, South Africa

Produces: Gold, Platinum & Diamonds

Extra-Terrestrial Impact Crater Mining for Resources



Lunar Craters were formed by constant bombardment from Asteroids, Comets and other Space Debris since the Solar System formation 4.5 Billion Years ago

Surfaces of Earth's Moon, Mars, Comet Temple 1 and Titan

Impact Craters can point us to the Resources:
O_2, PGM, Titanium, Aluminum, Iron H_2O, Volatiles

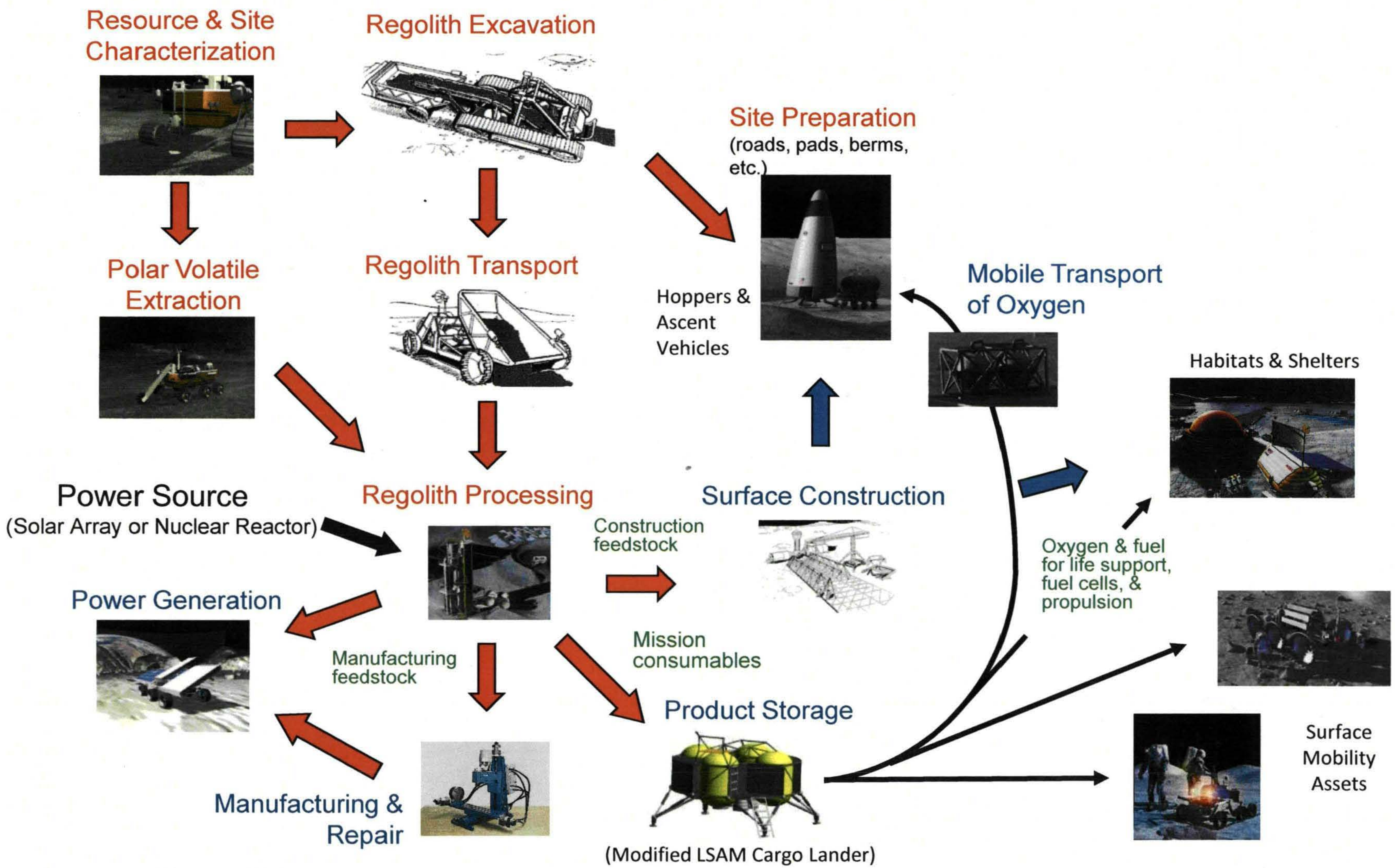
In-Situ Resource Utilization (ISRU)

When considering all aspects of ISRU, there are 5 main areas that are relevant to human lunar and Mars exploration (Sanders et al, 2010):

1. **Resource characterization and mapping for planning and science**
2. **In-situ production of mission critical consumables and propellants for crew, power, and transportation**
3. **Civil engineering and construction for hardware and crew protection and infrastructure growth**
4. **In-situ energy production and storage**
5. **In-situ manufacturing, repair, and reuse**

Areas 1, 2,3 and 5 require Regolith Operations and/or Regolith Mining

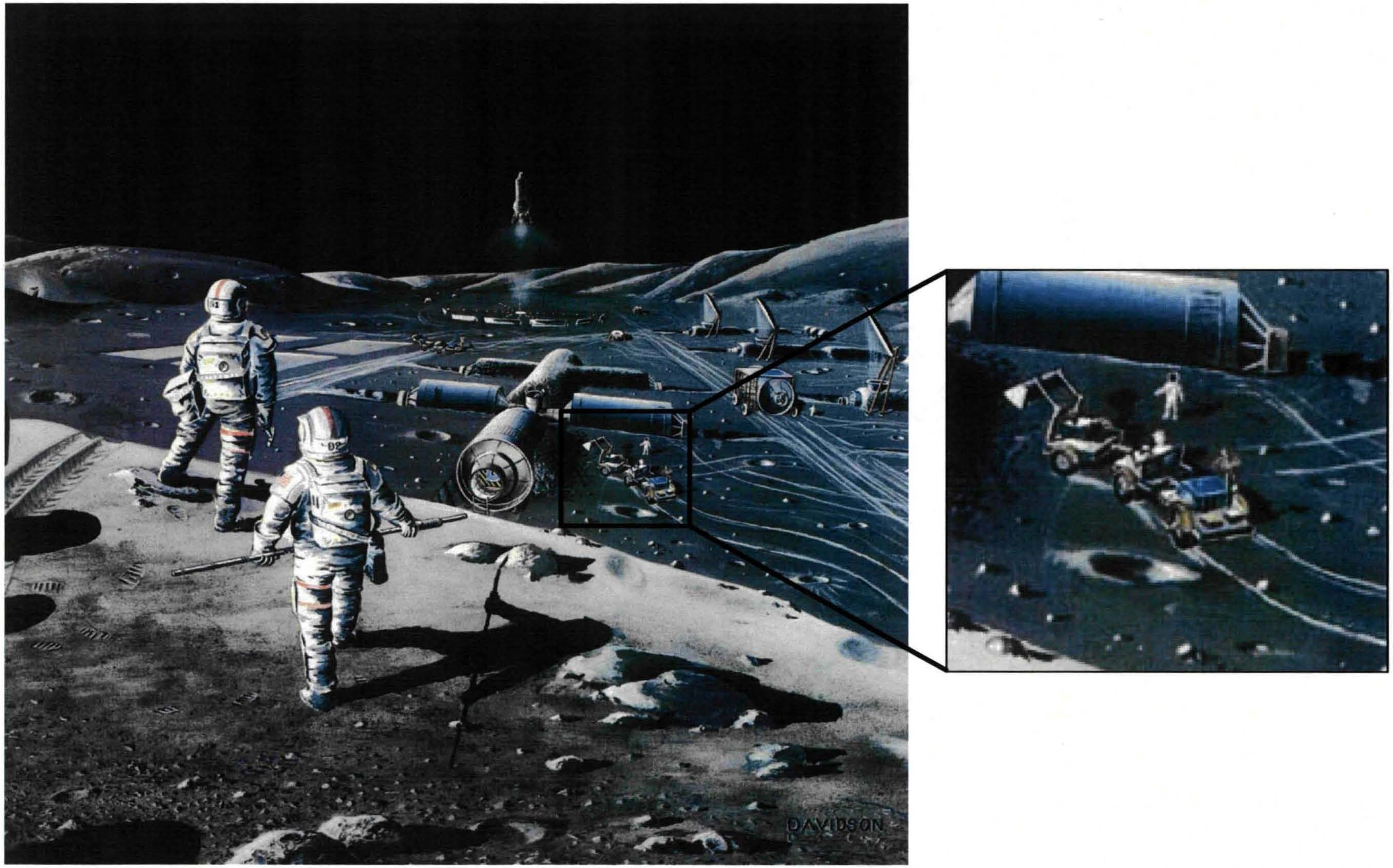
In-Situ Resource Utilization (ISRU)



Terrestrial Robotic Mining

- Increased safety and improved working conditions for personnel
- Improved utilization by allowing continuous operation during shift changes
- Improved productivity through real-time monitoring and control of production loading and hauling processes
- Improved draw control through accurate execution of the production plan and collection of production data
- Lower maintenance costs through smooth operation of equipment and reduced damage
- Remote tele-operation of equipment in extreme environments
- Deeper mining operations with automated equipment
- Lower operation costs through reduced operating labor
- Reduced transportation and logistics costs for personnel at remote locations
- Control of multiple machines by one tele-operator human supervisor

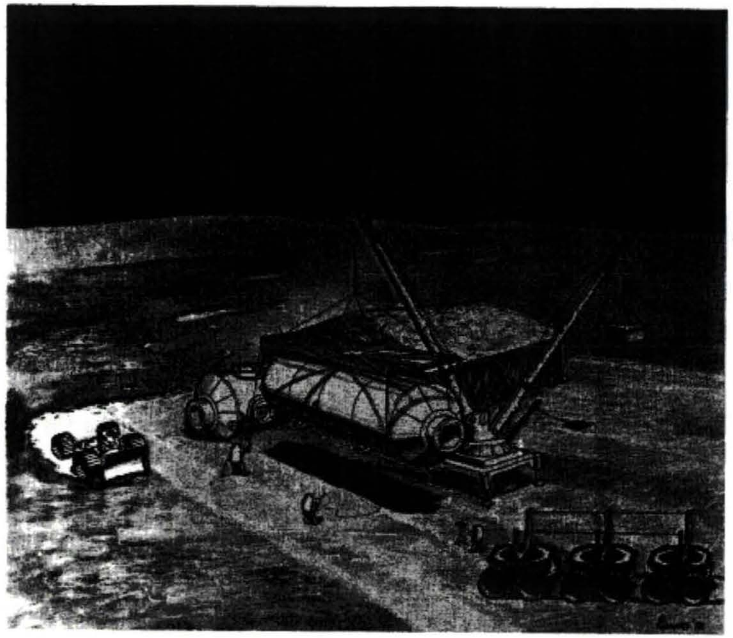
Early Visionary Studies 1900- 1980's



Eagle Engineering Reports -1988

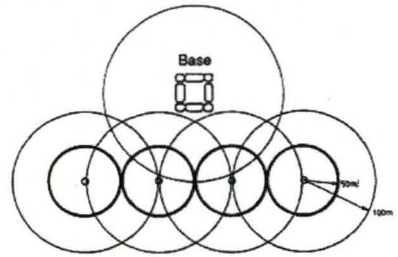
LBSS

Lunar Surface Construction & Assembly Equipment Study

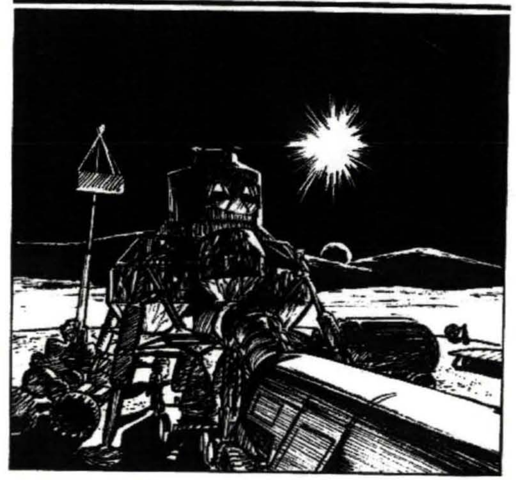


EEI Report Number 88-194
NASA Contract Number NAS 9-17878
1 September, 1988

EAGLE



Lunar Base Launch and Landing Facility Conceptual Design

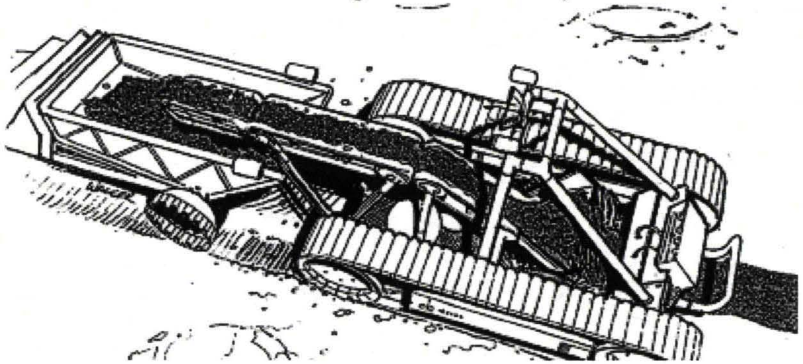


NASA Contract Number NAS9-17878
EEI Report 88-178

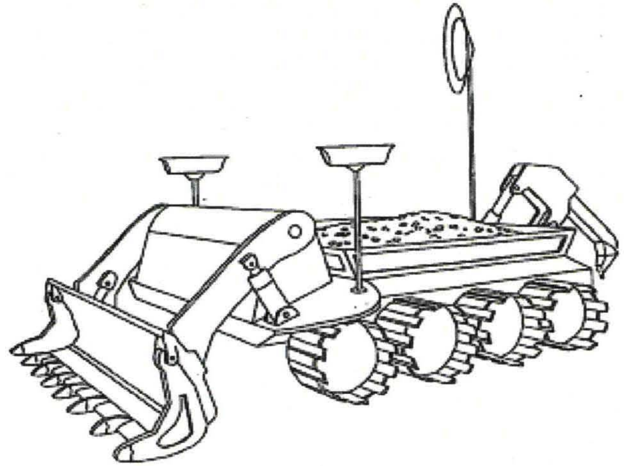
EAGLE

Space Exploration Initiative: 1989-1991
Planet Surface Systems Office – NASA JSC

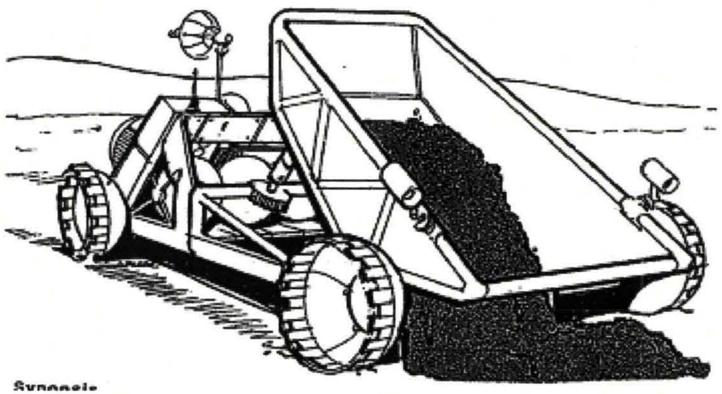
Mining Excavator/Loader, Lunar



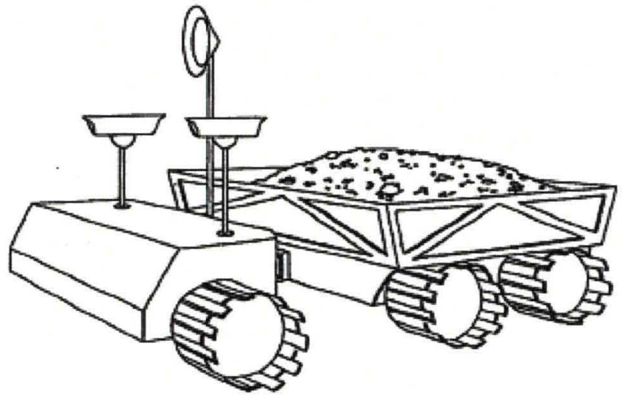
Ripper/Excavator/Loader



Regolith Hauler, Lunar



Articulated Hauler

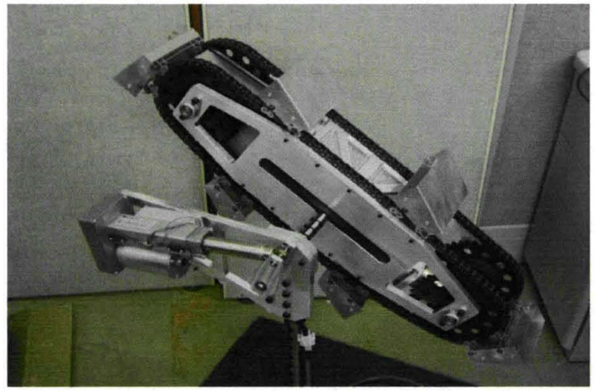


Lunar Underground -1990's

ASCE Earth & Space

Colorado School of Mines 2001 - 2011

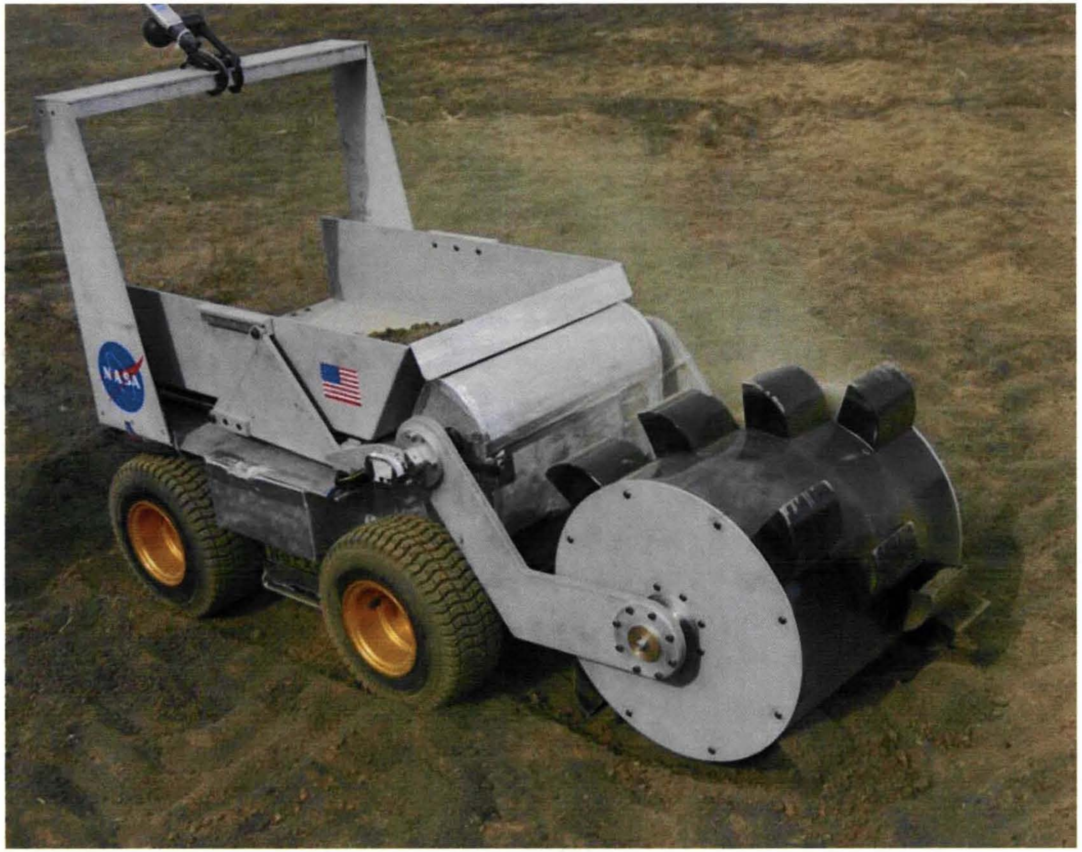
Mike Duke Project



Paul van Susante Projects

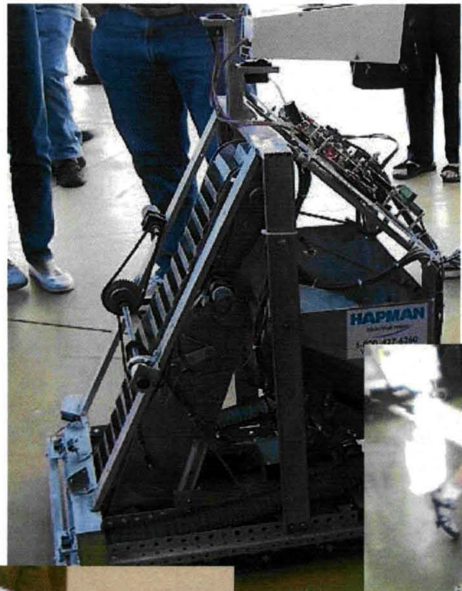
SysRand NASA SBIR

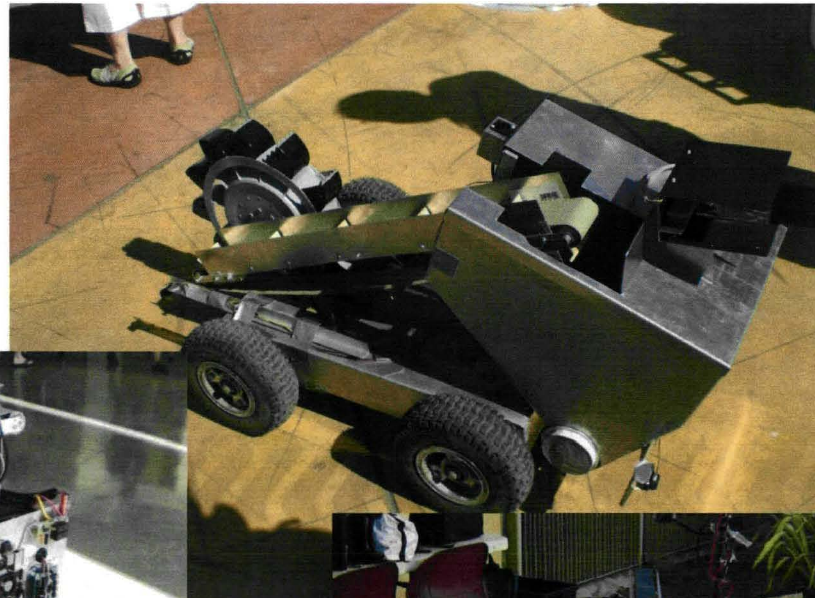
Lockheed Martin Bucket Drum - 2008

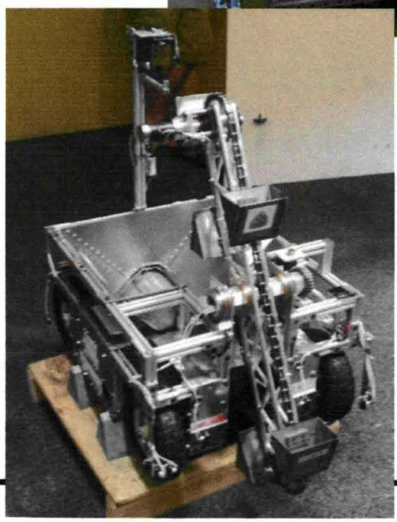


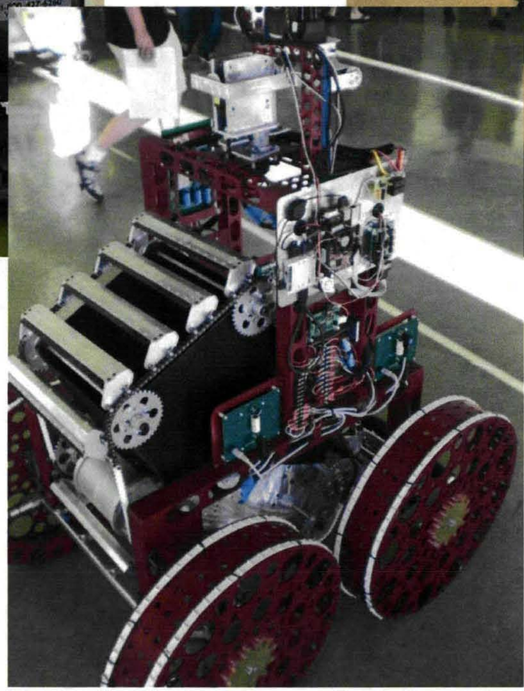
Lockheed Martin Corp. Bucket Drum Excavator (BDE) prototype.

NASA Centennial Challenge
Regolith Excavation Competition 2007-2009

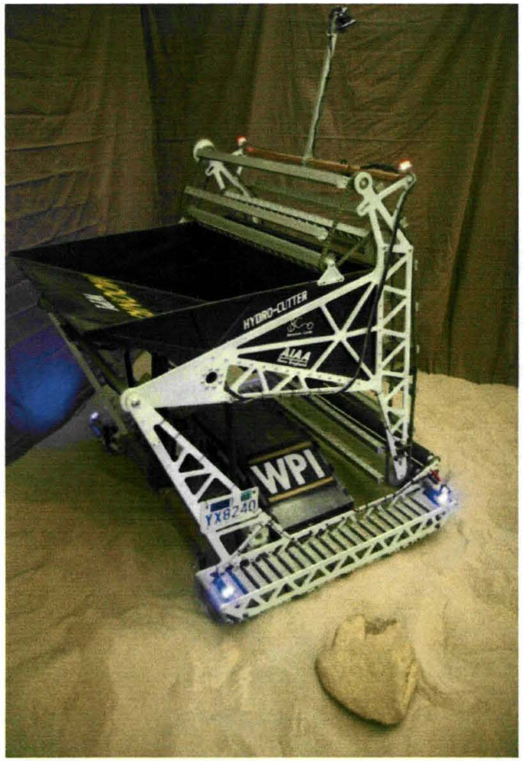


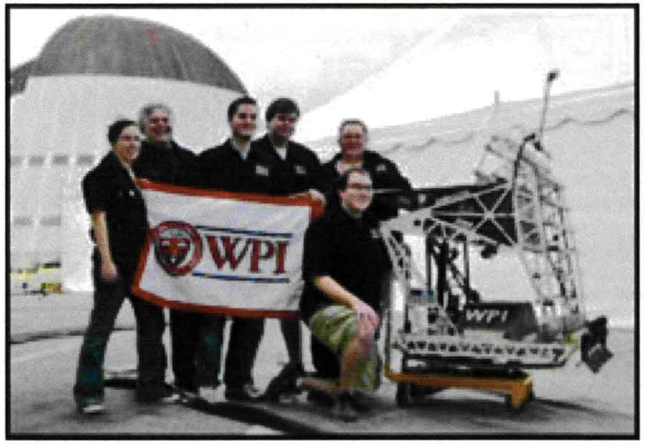




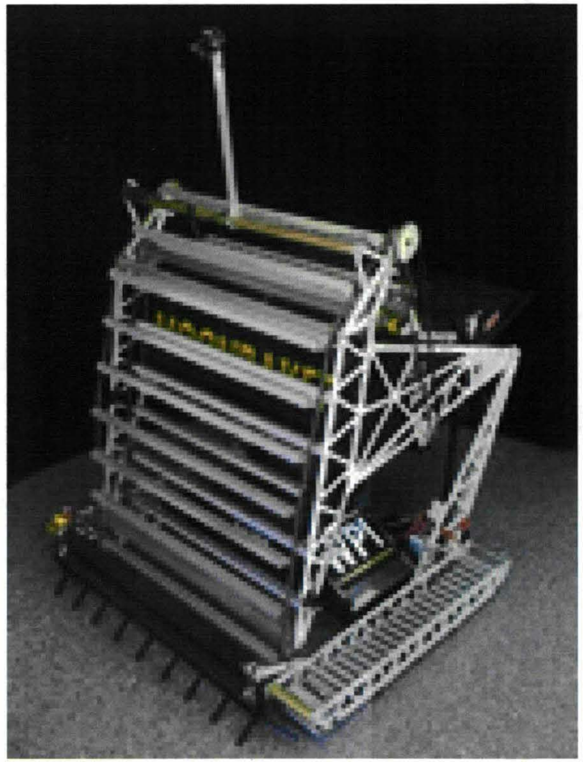


NASA Centennial Challenge
Regolith Excavation Competition Winner 2009



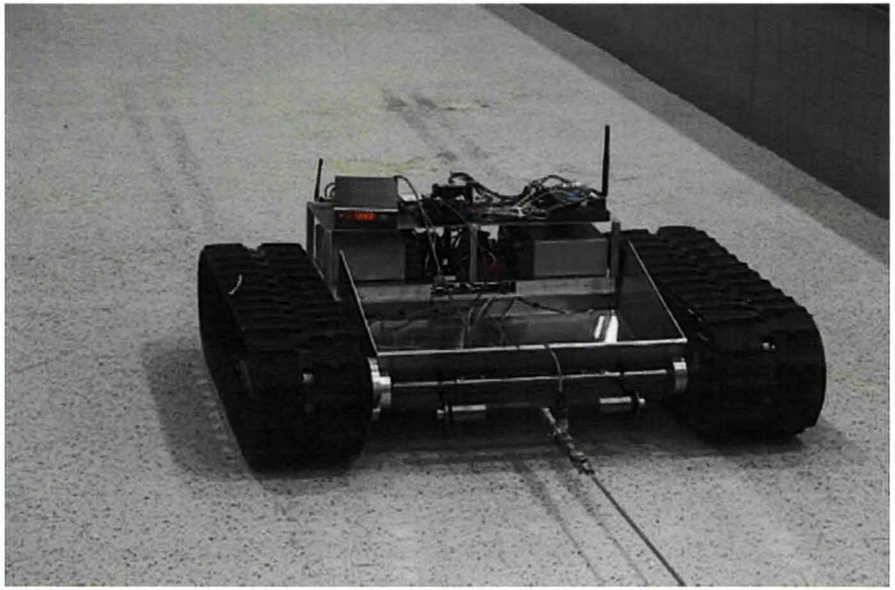


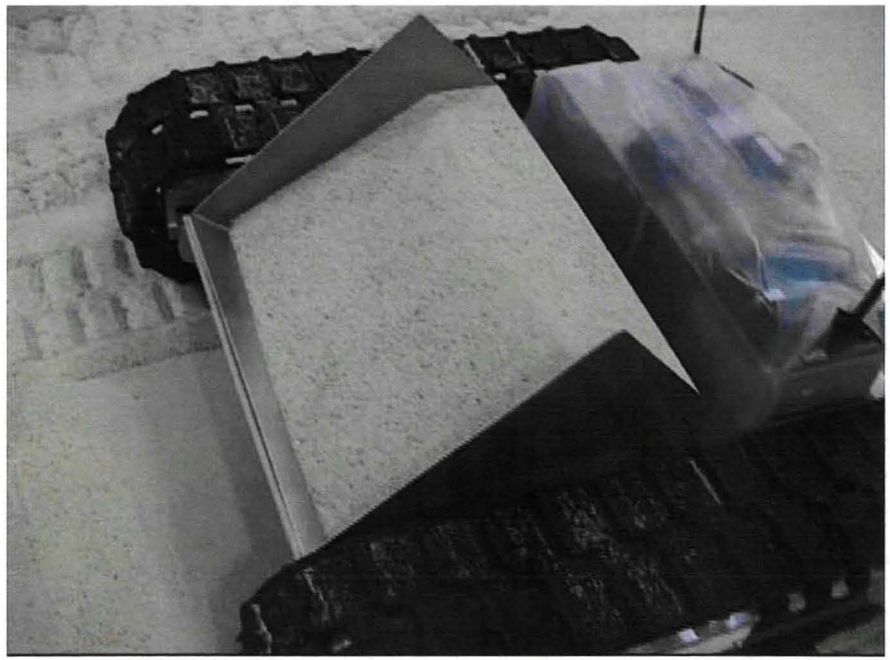
Paul's Robotics Centennial Challenges Winner,
Worcester Polytechnic Institute (WPI),
Worcester, Massachusetts



$500,000 Prize !

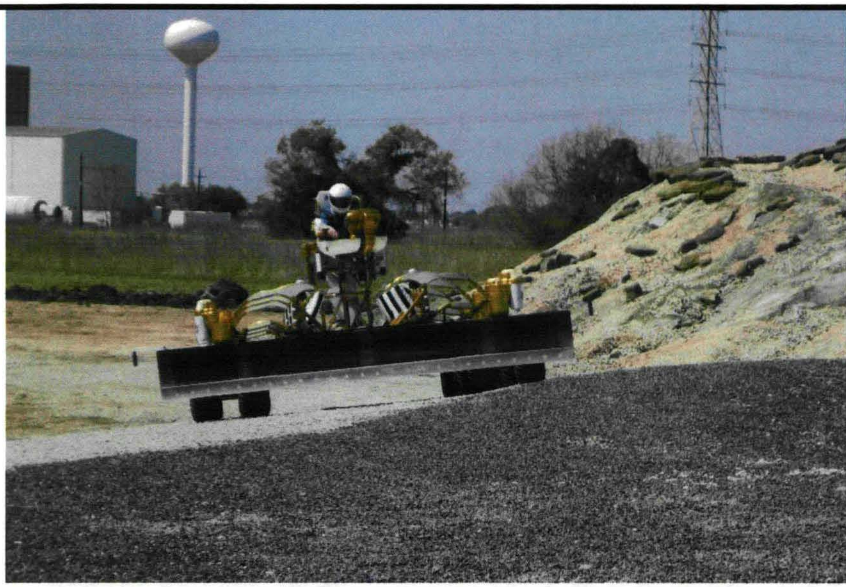
NASA Cratos – 2007
Glenn Research Center



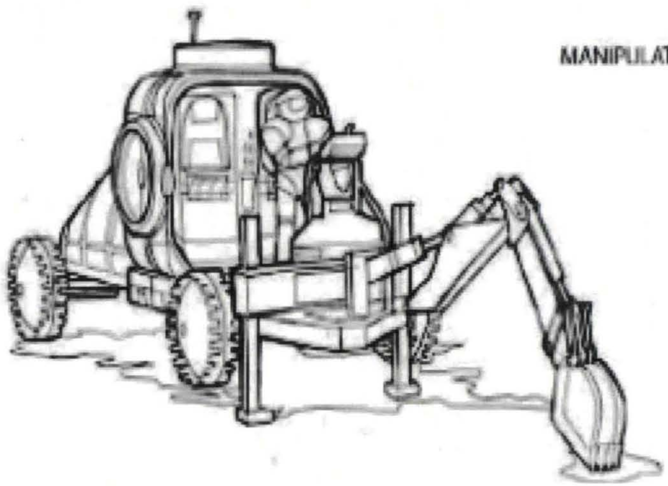


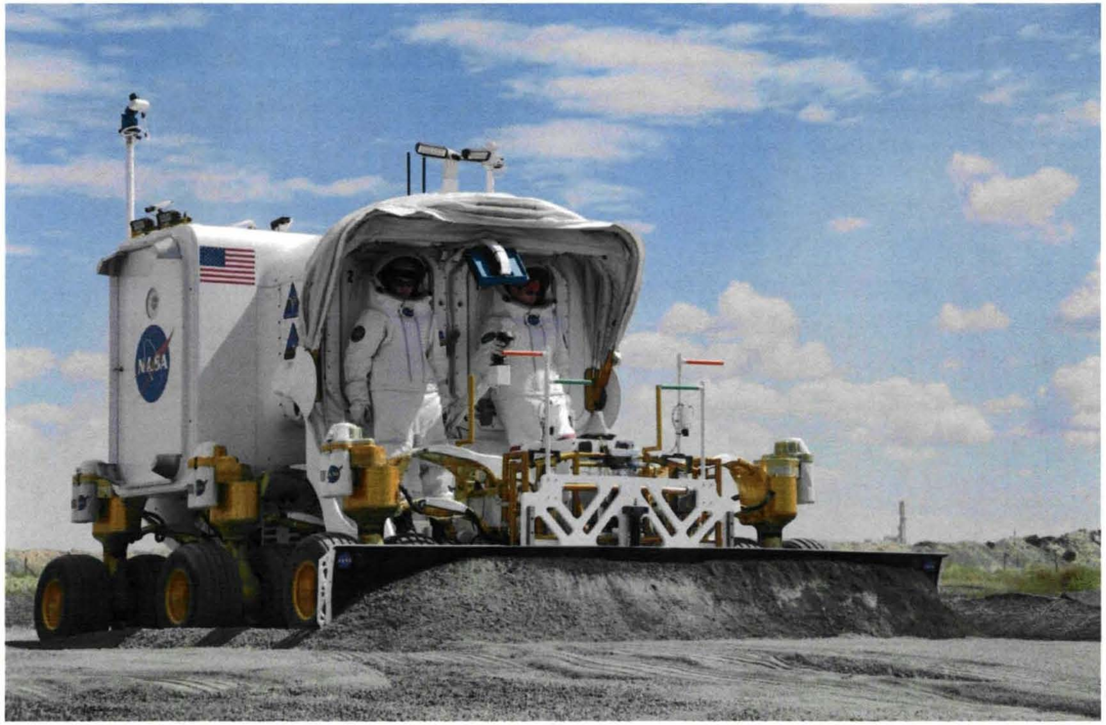
Lunar Attachment Node for Construction & Excavation (LANCE) on Chariot – NASA JSC/KSC 2009

Lunar Attachment Node for Construction & Excavation (LANCE) on Chariot – NASA 2009



Space Exploration Vehicle (SEV) 2010-2012





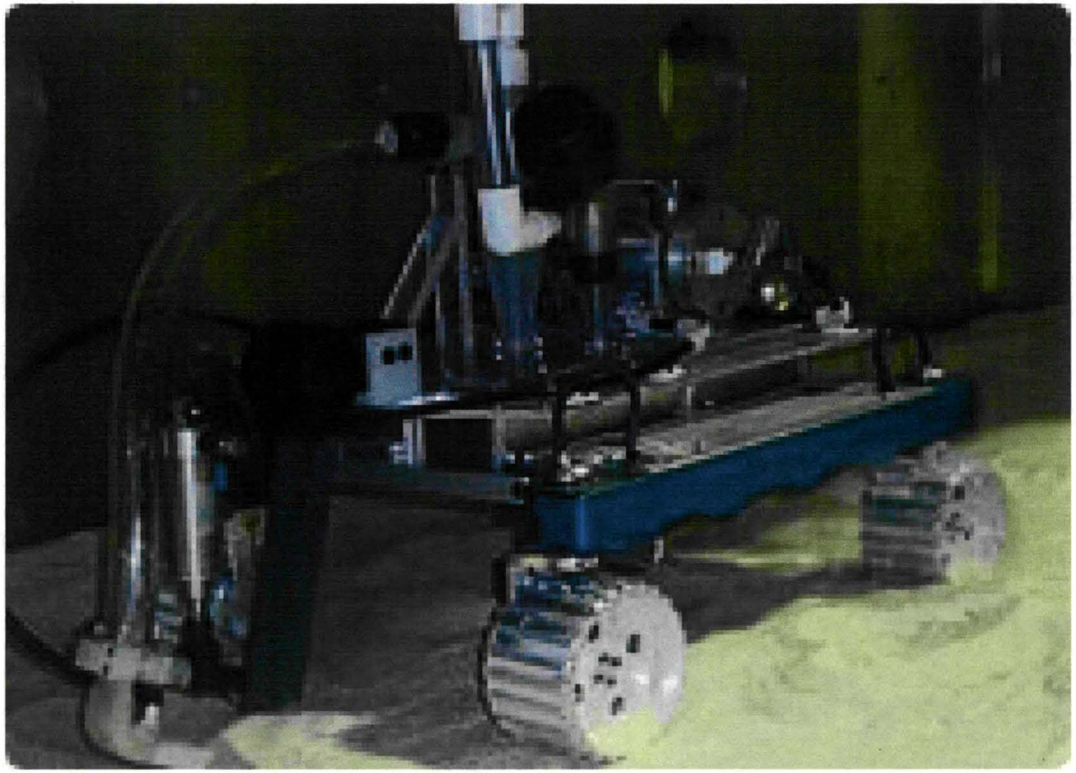
ATHLETE Excavation, NASA : 2009 - 2011

Automated Mining for Earth & Space
NASA/Caterpillar - 2009

Caterpillar 287C semi-autonomous Multi Terrain Loader

NASA Centaur 2 Regolith Excavator
JSC/GRC/KSC – 2010-2011

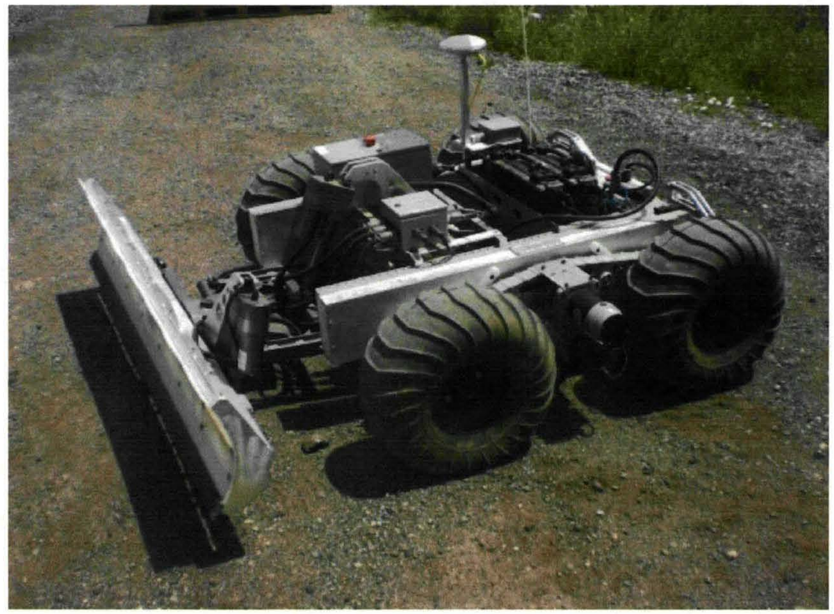
Pneumatic Excavation and Regolith Transport
Honeybee Robotics and NASA KSC: 2009-2011



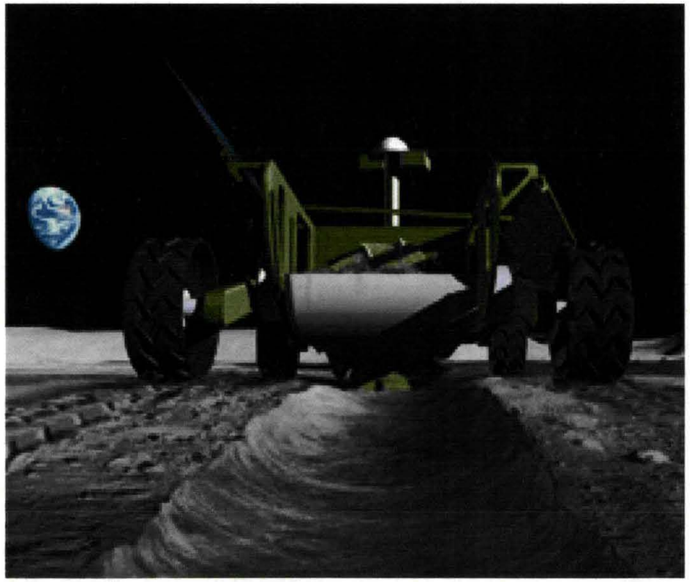
Canadian Space Agency, 2010 Mauna Kea ISRU Tests (NORCAT & Juno NEPTEC Rover)

Load, Haul, Dump Excavator

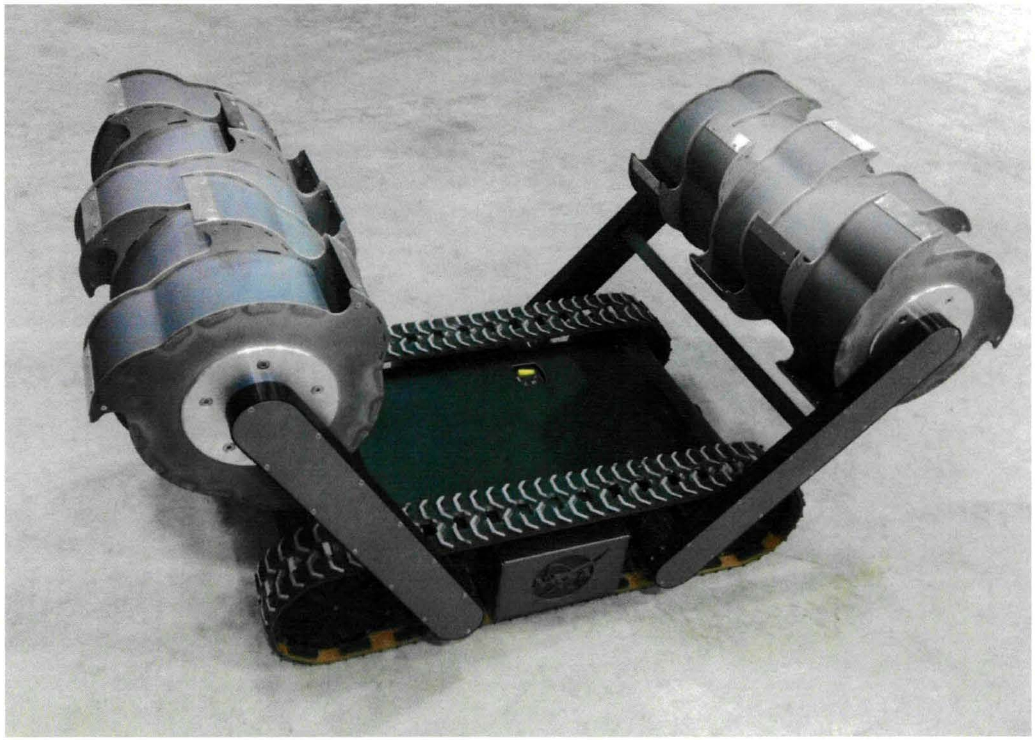
Small Bulldozer



Astrobotic Technology inc. Lunar Mining Concepts
NASA SBIR 2010-2012



Robotic Precursor Small Robotic Mining Systems (< 50 Kg) 2011-2012



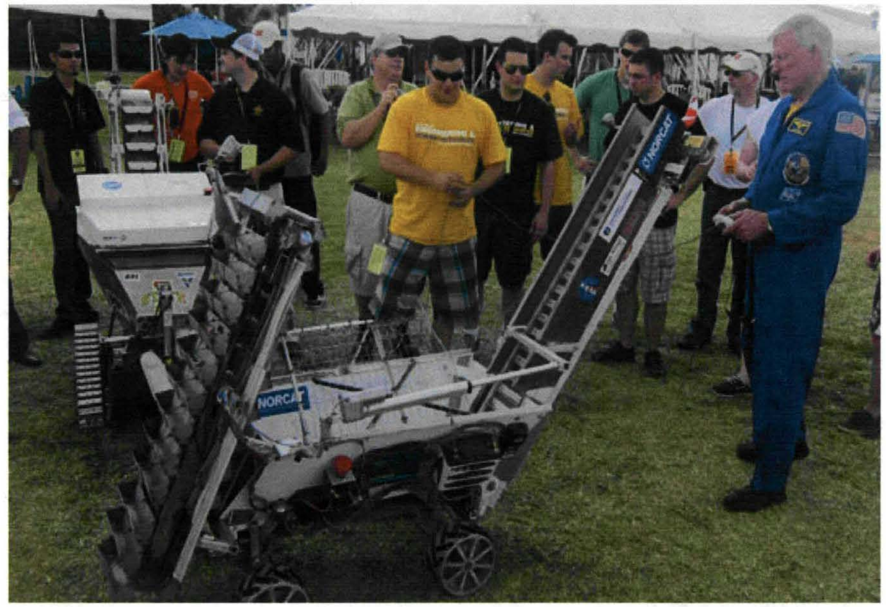
NASA Kennedy Space Center Excavator.
Regolith Advanced Surface Systems Operations Robot (RASSOR)

Regolith Excavation Mechanisms

All excavators from three Centennial Excavation Challenge Competitions (2007, 2008 and 2009) and two Lunabotics Mining Competitions (2010 and 2011)

Regolith Excavation Mechanism	# of machines employing excavation mechanism
Bucket ladder (two chains)	29
Bucket belt	10
Bulldozer	10
Scraper	8
Auger plus conveyor belt / impeller	4
Backhoe	4
Bucket ladder (one chain)	4
Bucket wheel	4
Bucket drum	3
Claw / gripper scoop	2
Drums with metal plates (street sweeper)	2
Bucket ladder (four chains)	1
Magnetic wheels with scraper	1
Rotating tube entrance	1
Vertical auger	1

NASA Lunabotics Mining Competition Robot Systems 2010 - 2012



2010 Lunabotics Mining Competition Winner: Montana State University "The Mule" Lunabot, from Bozeman, Montana

2011 Lunabotics Mining Competition Winner: Laurentian University "Production" Lunabot, from Sudbury, Canada

Top Robotic Technical Challenges*

- Object Recognition and Pose Estimation
- Fusing vision, tactile and force control for manipulation
- Achieving human-like performance for piloting vehicles
- Access to extreme terrain in zero, micro and reduced gravity
- Grappling and anchoring to asteroids and non cooperating objects
- Exceeding human-like dexterous manipulation
- Full immersion, telepresence with haptic and multi modal sensor feedback
- Understanding and expressing intent between humans and robots
- Verification of Autonomous Systems
- Supervised autonomy of force/contact tasks across time delay
- Rendezvous, proximity operations and docking in extreme conditions
- Mobile manipulation that is safe for working with and near humans

*NASA Technology Area 4 Roadmap: Robotics, Tele-Robotics and Autonomous Systems (NASA, Ambrose, Wilcox et al, 2010)

Top Space Mining Technical Challenges

- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Encountering sub surface rock obstacles
- Long life and reliability
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of perennially shadowed craters
- Extreme access and mobility
- Extended night time operation and power storage
- Thermal management
- Robust communications

Conclusions

- There are vast amounts of resources in the solar system that will be useful to humans in space and possibly on Earth
- None of these resources can be exploited without the first necessary step of extra-terrestrial mining
- The necessary technologies for tele-robotic and autonomous mining have not matured sufficiently yet
- The current state of technology was assessed for terrestrial and extra-terrestrial mining and a taxonomy of robotic space mining mechanisms was presented which was based on current existing prototypes
- Terrestrial and extra-terrestrial mining methods and technologies are on the cusp of massive changes towards automation and autonomy for economic and safety reasons
- It is highly likely that these industries will benefit from mutual co-operation and technology transfer